PROSPECTS FOR ENHANCING SEP ARRAY PERFORMANCE*

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SUMMARY

Three advanced blanket design models, all employing the OAST thin cell, have been developed for potential incorporation into the SEP array. The beginning-of-life (BOL) specific power of these blankets ranges from 180 to 660 W/kg. Coupling these blanket designs to the baseline SEP array structure yields array specific powers of from 90 to 200 W/kg. It is shown that certain modifications to the SEP array structure, coupled with the advanced blanket designs, could allow the BOL specific power to reach approximately 250 W/kg.

INTRODUCTION

The Solar Electric Propulsion (SEP) array developed by LMSC for NASA-MSFC represents the most advanced technology now in existence for producing photovoltaic power in space. The current design is rated at 66 W/kg beginning-of-life (BOL), and is capable of delivering at least 12.5 kw per wing (Ref. 1) The purpose of this paper is to describe approaches which can improve the performance of the SEP array with respect to specific power.

This analysis scrupulously avoids any consideration of end-of-life (EOL) specific power. There are a variety of reasons for this tack. The purpose of this work is to determine reasonable limits for planar solar array technology. Therefore, trends are more important than precise determinations. There are many mission classes, each with its own set of unique requirements and particular EOL definition. Admittedly, this will certainly have a strong influence on both blanket and structure design, but in the interests of clarity, this study will be confined to BOL conditions to avoid changing the blanket design to accomodate a particular mission.

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As presently configured, the SEP array has a mass of 379 kg, with the blanket accounting for 235 kg, while the support structure, deployment mechanism and container make up the remaining 144 kg of mass. As originally designed, the SEP blanket employed a very advanced, for its time, silicon solar cell. During the period in which the SEP array was brought to technical readiness, there has been dramatic progress made in improving silicon solar cell power output and mass. As a result, it is now possible to project that the SEP blanket can be modified to achieve a specific power approaching 650 W/kg. Coupling this blanket with a more refined array structure could yield a system rated at greater than 250 W/kg BOL.

The key to blanket improvement is the NASA-OAST thin silicon solar cell developed for NASA-JPL by the Solarex Corp (Ref. 2). Pilot production of this 50μm thick cell has demonstrated that the device can be manufactured in volume (>10,000 2 x 2 cm cells per month) with an AMO efficiency of 12 percent (Ref.3). Other versions of the cell, developed by space qualified suppliers, have shown conversion efficiencies approaching 15 percent (Ref. 4). Three blanket designs employing pilot production and more sophisticated variations of 50μ m cell technology are described in the following section of this paper. Based on the specific power of these blanket models, allowable reductions in the mass of the SEP array structure are projected. From this it is possible to estimate the upper limit for the SEP array BOL specific power.

BLANKET 1

This design employs the presently available OAST pilot production thin cell. A mass breakdown of the blanket is given in Table 1. An additional 5 kg increment per wing is assumed for each blanket model to account for the mass of the hinges, padding, stiffeners and other miscellaneous mechanical apparatus required for the proper functioning of the SEP baseline blanket design. A prototype module, very similar in design to blanket 1, has been produced for JPL by TRW (Ref.5), and is currently undergoing preliminary testing at MSFC prior to being incorporated into the SEP deployment and wing retraction space experiment. Blanket 1 uses planar rather than wraparound contact cells. Other major differences are the use of 50μ m ceria-doped microsheet covers and silver plated Invar in-plane interconnectors. The printed circuit substrate laminate used in the SEP blanket has been replaced in this design by a 50μ m Kapton sheet.

The approach taken in calculating the specific power of the three blanket models is to assume that the blankets are merely substituted in place of the current SEP design. Therefore, in each case the amount of power per wing will be different since the number of cells is held constant. A blanket packing factor of 80 percent is used to obtain the number of cells per wing. A power loss of 4 percent due to assembly and cell mismatching is used for this calculation. The circuit is assumed to be operating off the maximum power point which introduces an additional 6 percent penalty in the output power of the cell. These conditions are held constant for each blanket model. For blanket 1, which employs cells with no back surface reflectors, the blanket operating temperature is assumed to be 55°C, resulting in a further reduction in cell output.

Based on this set of assumptions, the BOL specific power of blanket 1 is calculated to be 182 W/kg for the 12 percent OAST thin cell case. Using the SEP array structure mass as a baseline, the array would now have a BOL specific power of 91 W/kg at operating temperature and deliver 13 kw per wing. Reductions in the mass of the array structure, now possible because of the lower blanket mass, would lead to further improvements in the array's specific power. Some of the estimates of the mass reduction that could be achieved in the SEP array structure elements are provided in a subsequent section of this paper.

BLANKET 2

This model, the details of which are provided in Table 2, represents a logical extension of existing blanket technology. An examination of the first model shows that the mass of the interconnect, cell contacts and plating contribute over 30 percent to the total blanket mass. In this model, therefore, the specific power is increased, by not only using a more efficient cell, but also seeking to significantly reduce the mass of the cell contacts and interconnect.

The cell employed in blanket 2 is a higher efficiency version of the pilot production OAST thin cell. Since conversion efficiencies greater than 14 percent AMO have already been demonstrated (Ref. 4), the choice of a 14 percent cell is justified. Two new technologies are incorporated into this cell, a gridded back contact to reduce mass and a back surface reflector (BSR) to decrease the cell absorbtivity. It has been reported that absorptances as low as 0.60 are possible when BSR technology is utilized (Ref. 6). Calculations show that an optimized BSR could reduce the cell operating temperature by 25°C.

Further mass reductions are achieved by substituting aluminum interconnects and significantly reducing the amount of silver plating on them. It should be mentioned that the present SEP blanket has copper interconnects and that aluminum had been seriously considered as a low mass alternate. If this blanket were to be operated in geosynchronous orbit where much wider thermal excursions are encountered, it might be necessary to retain the blanket 1 interconnect material.

The cell contact thickness has been reduced from 10 μm, employed in the first model, to 5 μm, since it is felt that welding silver plated aluminum to silver will present fewer challenges, due to the types of metals involved. The gridded back contact would be no problem, since OAST thin cells are made with back surface fields which result in a highly conducting silicon surface. Other elements where mass reduction can be achieved are in the amount of adhesive used to mount the cell to the substrate and the area of the interconnector design. Since these are minor influences, in this model they are held constant.

Using the same factors for assembly loss and off-maximum power point operation, the BOL specific power of blanket 2 is calculated to be 331 W/kg. Each wing now is capable of delivering 17 kw under operating conditions, due to the combination of a higher efficiency cell operating at a much lower temperature. Once again, the mass of the baseline SEP array structure is used to obtain the BOL specific power of the array, which for this model is 138 W/kg.

BLANKET 3

The previous models were based entirely on technology which has been demonstrated in one form or another. In this model, an attempt is made to estimate the ultimate BOL specific power that might be obtained from a planar silicon solar cell blanket. Table 3 shows the mass breakdown for such a blanket. From Table 2, it can be seen that the cell cover and adhesives comprise approximately 35 percent of the blanket's mass. As in the case of blanket 2, this model attempts to increase specific power by increasing the power output and simultaneously decreasing the blanket mass.

Blanket 3 incorporates two new elements of technology, very high efficiency cells and encapsulants, both of which are now being actively investigated. The solar cell is projected to have a conversion efficiency approaching 18 percent. The rationale for choosing this value will be discussed. It has become apparent in recent years that the last remaining barrier to achieving the practical upper limit for silicon solar cell efficiency is open circuit voltage (V_{OC}). It has been predicted that a V_{OC} of 700 mV is feasible (Ref.7). Combining this value with what has already been accomplished with respect to short circuit current and curve fill factor, yields an efficiency of approximately 18 percent AM0. At this point, it appears that success in obtaining a very high V_{OC} will not be partial. Therefore, it is assumed for this model that the mechanism controlling the V_{OC} in silicon solar cells will be understood and successfully exploited. In the event that this does not occur, it would seem unlikely that practical conversion efficiencies for silicon solar cells much greater than that used in blanket 2 will be achieved.

There is another approach which can be taken to obtain an upper limit for silicon blanket technology. Silicon solar cells of 25 μm thickness have been fabricated with conversion efficiencies greater than 12 percent AMO (Ref. 8). Employing a cell of this type in place of the extremely high output cell upon which this model is based would result in a blanket specific power only about 15 percent lower than in the case of using an 18 percent 50μm thick OAST thin cell.

In this model, the cell thickness has been reduced to 50 μm. Some allowance for handling problems caused by the use of very thin cells had been made in the previous models. However, since traditional methods of covering cells are not assumed for blanket 3, the cell thickness is taken to be 50 μm. There may be some objection to projecting extremely high efficiencies for very thin cells, but at present, there is no significant difference in output between ultrathin and conventional thickness cells. It is not expected that the mechanism controlling V_{OC} will be related to cell thickness; in fact, according to some theorists (Ref. 9), an ultrathin cell may be a better configuration for obtaining high V_{OC} in silicon solar cells.

The second major element of new technology is the use of an encapsulating material which will replace both the present Kapton substrate and the ceria-doped microsheet covers of the previous designs. A great deal of work has already been done in the area of encapsulants (Ref. 10,11) and the development of ultrathin solar cells has provided further stimulus. The encapsulant used in blanket 3 is not a glass, but rather a transparent, ultraviolet resistant, organic material which can be provided in sheet form and is capable of being joined without the use of primers or adhesives which would add mass to the blanket. The advantages of such a material are obvious with respect to blanket fabrication.

The choice of encapsulant thickness is somewhat arbitrary. The encapsulant should have a thickness equivalent to that of 25μ m of fused silica in order to provide sufficient shielding to protect the cells from low energy proton degradation. Obviously, the radiation environment encountered during the mission and the inherent radiation resistance of the cell used will be the determining factors in selecting the amount of shielding required for both the front and rear sides of the blanket.

Further reductions in blanket mass may be achieved by replacing the silver contact system with aluminum. It has been demonstrated that the aluminum contact system is viable for silicon cells (Ref. 12,13), although at that time the cell junction was much deeper than currently used. The thickness of the interconnect could be reduced to 12 μm. In fact, there is evidence available to indicate that 12 μm interconnects are more compatible with ultrathin cells (Ref. 14). There is some risk that with very high efficiency cells, there might be an undesirable voltage drop in the circuits due to the narrow cross sectional area of this interconnect. However, for this exercise, both modifications have been incorporated into the blanket 3 model.

Blanket 3 has a calculated BOL specific power of 660 W/kg. As in the previous cases, the assumptions concerning packing factor, assembly loss and off-maximum power operating point have been held constant. Using the present SEP array structure mass of 72 kg per wing, the BOL specific power at the array level is increased to 205 W/kg with each wing delivering 21.5 kW. This blanket results in a greater than threefold improvement in BOL specific power from the SEP array as it is presently designed.

STRUCTURAL CONSIDERATIONS

Additional improvements in BOL specific power at the array level can only be realistically achieved by reducing the mass of the structure which is used to store, deploy, tension and support the blanket. In the case of the SEP array, great caution must be exercised in choosing areas which may show potential for mass reduction. This particular array has many unique features, such as the ability to partially or fully retract. In addition, the system is designed to be capable of operating over a wide thermal environment, since it must function from 0.3 to 6.0 AU. The natural frequency requirement acts as a further constraint. Thus, it should be obvious that reducing structure mass is not a straightforward task.

An examination of the principal components making up the array structure shows that the mast and its cannister are responsible for half of the total array structure mass. This would therefore appear to be a logical place for mass savings. Due to the lower mass of the blanket, it might be possible to resize the diameter of the mast. In doing so, it may create a situation which allows the cannister volume to be reduced, saving additional mass. There is also the distinct possibility that portions of these elements could be constructed with alternate materials which have a lower density. However, it is not possible to make quantitative projections of mass reduction without a great deal of additional information concerning the effects of these potential adjustments on the dynamic and thermal characteristics of the array.

Another major contribution to the structure mass ($\sim$25 percent) comes from the container and cover which are used to store and maintain the blanket properly during launch and re-entry. These items are basically static and therefore probably have a smaller impact on the operating characteristics of the array. Since in this exercise, the blanket volume has not been changed, it is unlikely that the container or cover can be resized. There is the possibility that lower mass materials of construction can be employed. However, the critical properties of these components, such as rigidity and strength, cannot be compromised.

In order to provide some estimate of the impact of structure mass reduction on the BOL performance of this array, a plot of array specific power as a function of structure mass is provided in Figure 1. Four blanket cases are presented, the baseline SEP design and the three models described in the preceding sections of this paper. The choice of the mass reduction range is somewhat arbitrary, and does not imply that these are reasonable limits to which the structure mass can be reduced.

CONCLUSIONS

It would appear from this analysis that the SEP array has the potential to achieve a BOL specific power of between 200 and 250 W/kg. It is likely that this would be reached by a combination of a higher performance blanket in conjunction with some modifications in array structure. The most important conclusion is that, in this case, progress in blanket development seems to offer a greater return as far as array performance improvement is concerned. Reduction to practice of the elements comprising blanket 2 would double the performance capabilities of the SEP array. There would be no realistic way to match this improvement by modifying structure. It is also apparent that if arrays capable of achieving greater than 250 W/kg at BOL are required, new concepts in array design must be developed.

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TABLE I

SILICON BLANKET 1 MASS BREAKDOWN (125 M^2 WING AREA)

ELEMENT	DESCRIPTION t(μ m)	MASS (KG/M^2)	NOTES
Substrate	50 Kapton	.072	
Adhesives	25 DC 93-500	.049	Substrate & Cover
Solar Cell	62 Silicon	.115	80% Packing Factor
Cell Contacts	10 Silver	.088	
Cell Cover	50 CMS	.101	
Interconnect	25 Invar	.052	
IC Plating	20 Silver	.054	
Misc.	-------	.040	Padding, Stiffeners, etc.
TOTAL		.571	

TABLE II

SILICON BLANKET 2 MASS BREAKDOWN (125 M^2 WING AREA)

ELEMENT	DESCRIPTION t(μ m)	MASS (KG/M^2)	NOTES
Substrate	50 Kapton	.072	
Adhesives	25 DC 93-500	.049	Substrate & Cover
Solar Cell	62 Silicon	.115	80% Packing Factor
Cell Contacts	5 Silver	.013	20% Back Coverage
Cell Cover	50 CMS	.101	80% Packing Factor
Interconnect	25 Aluminum	.018	
IC Plating	1 Silver	.003	
Misc.	-----	.040	Padding, Stiffeners, etc.
TOTAL		.411	

TABLE III

SILICON BLANKET 3 MASS BREAKDOWN (125 M^2 WING AREA)

ELEMENT	DESCRIPTION t(μ m)	MASS (KG/M^2)	NOTES
Substrate	25 Encapsulant	.056	Fused Silica Equivalent
Adhesives	-----	-0-	None Required
Solar Cell	50 Silicon	.093	80% Packing Factor
Cell Contacts	5 Aluminum	.003	20% Back Coverage
Cell Cover	25 Encapsulant	.056	Fused Silica Equivalent
Interconnect	12 Aluminum	.009	80% Packing Factor
I. C. Plating	1 Silver	.003	80% Packing Factor
Misc.	----	.040	Padding, Stiffeners, etc.
TOTAL		.260	

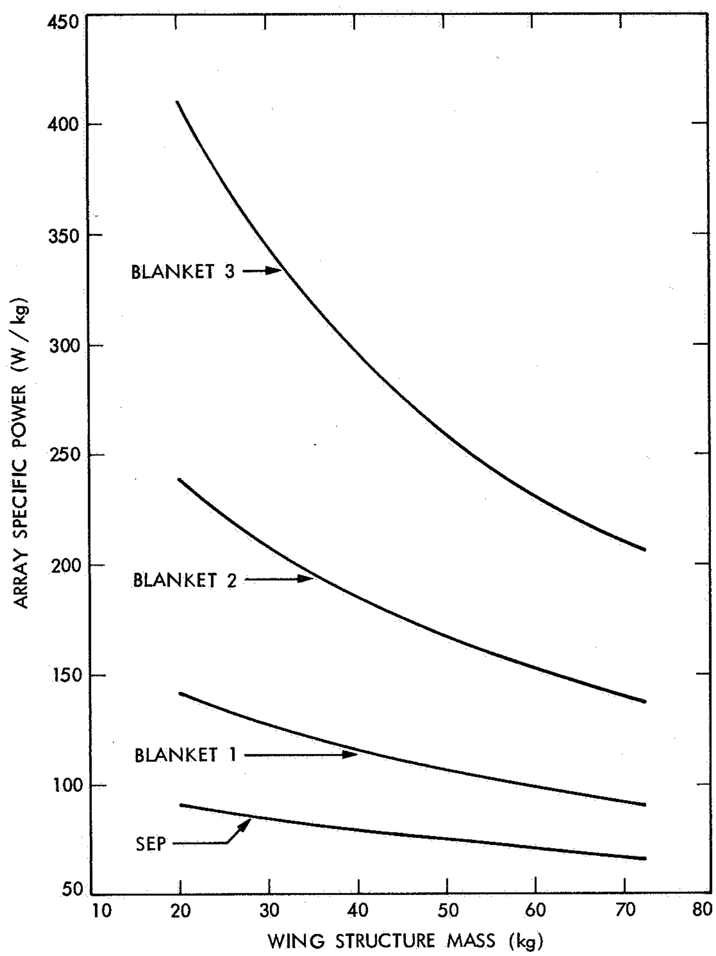

Figure 1. EFFECT OF STRUCTURAL MASS REDUCTION ON THE SPECIFIC POWER OF THE SEP ARRAY